Economics and Synergies of Electrolytic and Thermochemical Methods of Environmentally Benign Hydrogen Production

G. F. Naterer

This document appeared in

Detlef Stolten, Thomas Grube (Eds.):
18th World Hydrogen Energy Conference 2010 - WHEC 2010
Parallel Sessions Book 4: Storage Systems / Policy Perspectives, Initiatives and Co-operations
Proceedings of the WHEC, May 16.-21. 2010, Essen
Schriften des Forschungszentrums Jülich / Energy & Environment, Vol. 78-4
Institute of Energy Research - Fuel Cells (IEF-3)
Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag, 2010
ISBN: 978-3-89336-654-5

Economics and Synergies of Electrolytic and Thermochemical Methods of Environmentally Benign Hydrogen Production

G. F. Naterer, University of Ontario Institute of Technology, Canada

Abstract

Most of the world's hydrogen (about 97%) is currently derived from fossil fuels. For reduction of greenhouse gases, improvement of urban air quality, and energy security, among other reasons, carbon-free sources of hydrogen production are crucial to hydrogen becoming a significant energy carrier. Nuclear hydrogen production is a promising carbon-free alternative for large-scale, low-cost production of hydrogen in the future. Two nuclear technologies, applied in tandem, have a promising potential to generate hydrogen economically without leading to greenhouse gas emissions: 1) electrolysis and 2) thermochemical decomposition of water. This paper will investigate their unique complementary roles and economics of producing hydrogen, from a Canadian perspective. Together they can serve a unique potential for both de-centralized hydrogen needs in periods of low-demand electricity, and centralized base-load production from a nuclear station. Hydrogen production has a significantly higher thermal efficiency, but electrolysis can take advantage of low electricity prices during off-peak hours. By effectively linking these systems, water-based production of hydrogen can become more competitive against the predominant existing technology, SMR (steam-methane reforming).

1 Introduction

This paper examines the synergistic roles of electrolysis and thermochemical water decomposition, which together can provide a lower-cost sustainable supply of hydrogen than current technologies. In particular, thermochemical water decomposition, driven by nuclear heat with a copper-chlorine (Cu-Cl) cycle, splits water into hydrogen and oxygen through intermediate copper and chlorine compounds (Serban, Lewis, Basco; [1, 2], Naterer et al. [3 - 5]). Unlike other sustainable energy resources (e.g., solar, wind), nuclear heat used in this thermochemical cycle enables large-scale direct production of hydrogen. A Cu-Cl plant could be eventually linked with nuclear reactors to achieve higher efficiencies of hydrogen production than any other conventional technology. Recent advances in a hybrid Cu-Cl cycle linked with Canada's nuclear reactors were presented by Suppiah et al. [6].

Much effort internationally is being focused on the Sulfur-Iodine (S-I) cycle and its variations, as well as High-Temperature Electrolysis (HTE) for nuclear-based hydrogen production. The copper-chlorine (Cu-Cl) cycle offers a number of advantages over the S-I cycle, including lower operating temperatures, capability of utilizing low-grade waste heat from nuclear reactors and lower-cost materials. This paper examines the additional benefits of integrating electrolysis and thermochemical hydrogen production, due to their unique advantages of de-centralized off-peak and centralized base-load production, respectively, to reduce costs and

become more competitive against the predominant existing technology, SMR (steam-methane reforming).

2 Hydrogen Costs by Electrolysis

A case study of distributed hydrogen production by electrolysis was examined by Miller [7, 8] for hydrogen vehicles supplied by neighbourhood fueling stations. Costs were reported in 2002 US dollars, assuming a 15%/year return on investment and a 10-year amortization, which is approximately equivalent to an annual capital charge of 20%. A production cost of $300 /kW for the electrolysis cells was assumed, along with storage costs of $800,000 /tonne of hydrogen via tube storage.

The parameters of the case study are 600,000 vehicles that are fueled by hydrogen produced from a medium sized nuclear reactor (700 MW), which requires about 56 kWh per kilogram of hydrogen from electrolysis. The energy content of hydrogen is about three times higher than gasoline, weight for weight, and the conversion efficiency of a fuel cell versus ICE is about 2 to 2.5 times better. This implies an overall hydrogen to gasoline weight ratio of about 6 to 7.5. A typical fill-up scenario for a gasoline vehicle is 40 L (30 kg), equivalent to 3 kg of hydrogen, stored in 700-atmosphere aluminum carbon-fibre reinforced cylinders, occupying about 80 L. Given this fuel requirement and number of vehicles, the required supply of hydrogen can be determined, after which the continuous electrolysis supply becomes known. If off-peak electricity is used instead for electrolysis, then a threshold price is established, wherein hydrogen is only produced below the threshold. When this threshold price is lowered, more capacity of electrolysis is needed to produce a given quantity of hydrogen over a shorter duration. Also, more storage capacity is needed, due to longer periods without generation of hydrogen.

For a given threshold price, a larger electrolysis capacity implies less storage is needed to meet peak demand, but there is more expensive capacity of installed units and higher hydrogen cost. Conversely, less installation capacity requires more storage hours and higher storage costs. This again indicates an optimum exists at a particular electrolysis installation capacity, above which the price becomes excessive, per kg of hydrogen produced.

3 Hydrogen Costs with the Copper-Chlorine (Cu-Cl) Cycle

The Cu-Cl thermochemical cycle uses a series of reactions to achieve the overall splitting of water into hydrogen and oxygen. The chemical reactions form a closed internal loop that re-cycles all chemicals on a continuous basis, without emitting any greenhouse gases externally to the atmosphere.

Recent studies at the Argonne National Laboratory [9] quoted an approximate capital cost of $124M for a Cu-Cl plant that produces 125 tonnes/day of hydrogen. Using the power law for the capital cost of a chemical plant that varies with size raised to about the 0.66 power, to scale down the plant capacity to 10 tonnes/day, the capital cost becomes about $29M. This represents a future cost in 2015, when the current status of Cu-Cl technology can be scaled up to a pilot plant capacity. For consistency with past reported data for electrolysis [7, 8], the capital cost will be discounted back in time to account for 3% inflationary price changes over a decade. Multiplying the resulting capital cost by 20% for the annual capital charge, dividing

by the plant size (in tonnes per day), times 142 GJ /tonne and 365 days per year, yields a contribution of $7.7 /GJ for the capital portion of the hydrogen cost.

The cost of energy input for the thermochemical plant is heat from nuclear or other sources. Consider the following two approaches for this cost estimation. The first option uses natural gas for the high-temperature heat requirement of the Cu-Cl cycle, consuming about 40% of the net cycle heat input. Then using the previously quoted natural gas cost of 5$ /GJ, dividing by the cycle efficiency of 43%, multiplying by the high-grade heat portion, and finally adding the previously quoted distribution fee for natural gas, yields an energy cost of about 6.3$ /GJ. In practice, utilizing waste heat can raise the cycle's efficiency, and improving the internal re-cycling of heat can further reduce the high-grade heat requirement, both of which would lead to lower energy costs.

Unlike de-centralized electrolysis without distribution costs (hydrogen is generated locally at fueling stations), hydrogen needs to be transported from a centralized Cu-Cl plant to the fueling stations. Costs of truck transportation operating with compressed gas by tube trailer are about 4.6$ /GJ, for distances of about 16 km. Herein lies a key synergy between off-peak electrolysis and thermochemical production of hydrogen. The trucking costs rise with distance from the Cu-Cl plant, so thermochemical production is competitive in the vicinity of large cities, but de-centralized electrolysis (without transportation costs) has lower costs farther away in surrounding towns. In this way, electrolysis and thermochemical production have synergistic roles with each other, similarly to centralized base-load electricity with nuclear power, together with de-centralized supply from wind or solar power.

Alternatively, hydrogen can be distributed within a city by pipeline. However, these costs become higher and pipelines only become competitive when the demand grows to large capacities. The pipeline option can eventually carry much higher capacities of hydrogen at no additional cost. So there is an inversely proportional decrease in unit cost for higher capacities of hydrogen. Similar economic tradeoffs exist between electrolysis and thermochemical production with pipeline transportation. Shorter pipelines are needed between fueling stations in cities, whereas de-centralized electrolysis becomes more economically attractive in surrounding towns, since more expensive piping networks of hydrogen raise the costs of hydrogen.

4 Results and Discussion

This section will present results to demonstrate the synergistic roles of off-peak electrolysis and thermochemical production of hydrogen. The different methods have a unique potential to serve both de-centralized needs in off-peak hours, and centralized base-load production from a nuclear station, respectively. Thermochemical methods have significantly higher thermal efficiency, but electrolysis can take advantage of low electricity prices during off-peak hours, as well as intermittent and de-centralized supplies of electricity like wind, solar or tidal power. By effectively linking these systems, water-based production of hydrogen can become more competitive against the predominant existing technology, SMR (steam-methane reforming).

Figure 1 shows that thermochemical production becomes more competitive at larger capacities of hydrogen production. Below capacities of between about 10-20 tonnes/day,

electrolysis from off-peak electricity has a lower unit cost of hydrogen production, although the advantage reverses at higher capacities. Furthermore, electrolysis costs have taken advantage of off-peak electricity, so an analogous benefit could be realized with a Cu-Cl cycle linked with SCWR. For example, a certain base-load production of hydrogen can be maintained with SCWR, but a bypass heat exchanger could re-direct steam from the power turbine to the Cu-Cl plant during off-peak periods of low electricity demand. Discounting the energy cost by an equivalent amount as the off-peak electrolysis, a further potential cost reduction of $2.8 /GJ is illustrated in Figure 1. The legend shows ">$2.8 /GJ" because further discounts can be realized at a lower price threshold of off-peak electricity, although the corresponding storage costs rise. Various uncertainties, idealizations and simplified underlying assumptions have been used in this cost analysis, so the results are intended more to provide qualitative trends, rather than precise costs. A key result is the predicted cross-over point between electrolysis and thermochemical production, at about 10-20 tonnes/day. The emerging hydrogen economy will have many needs for both lower and higher capacities, so electrolysis and thermochemical methods will remain complementary to each other.

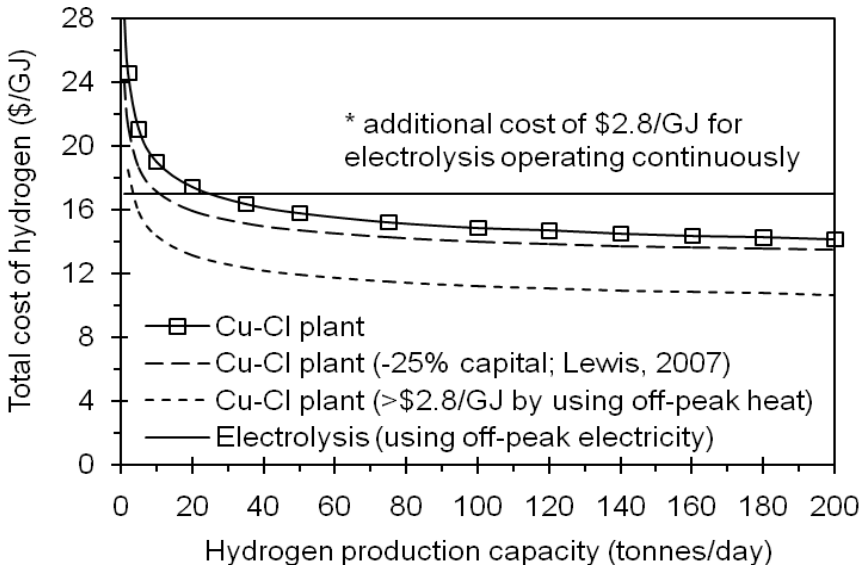

Figure 1: Comparison between electrolysis and thermochemical production methods.

5 Conclusions

This paper has examined the potential of electrolysis and thermochemical hydrogen production to serve both de-centralized needs with production during off-peak hours, and centralized base-load production from a nuclear station, respectively. Thermochemical methods have significantly higher thermal efficiency, but electrolysis can take advantage of low electricity prices during off-peak hours, local use of byproducts of heat and oxygen, as well as intermittent and de-centralized supplies of electricity like wind, solar or tidal power. By

effectively linking these systems, production of hydrogen from nuclear and/or renewable energy can become more competitive against the predominant existing technology, SMR.

Acknowledgements

Support of this research from Atomic Energy of Canada Limited, Ontario Research Fund and the Natural Sciences and Research Council of Canada (NSERC) is gratefully acknowledged.

References

[1] Serban, M., Lewis, M., Basco, J., “Kinetic Study of the Hydrogen and Oxygen Production Reactions in the Copper-Chloride Thermochemical Cycle”, AIChE 2004 Spring National Meeting, New Orleans, LA, April 25-29, 2004

[2] Lewis, M. A., Masin, J. G., Vilim, R. B., Serban, M., “Development of the Low Temperature Cu-Cl Thermochemical Cycle”, International Congress on Advances in Nuclear Power Plants, May 15 - 19, 2005, Seoul, Korea

[3] Naterer, G. F., Gabriel, K., Wang, Z., Daggupati, V., Gravelsins, “Thermochemical Hydrogen Production with a Copper-Chlorine Cycle, I: Oxygen Release from Copper Oxychloride Decomposition” (in press), International Journal of Hydrogen Energy, 2008

[4] Naterer, G. F., Daggupati, V., Marin, G., Gabriel, K., Wang, Z., “Thermochemical Hydrogen Production with a Copper-Chlorine Cycle, II: Flashing and Drying of Aqueous Cupric Chloride" (in press), International Journal of Hydrogen Energy, 2008

[5] Wang, Z., Naterer, G. F., Gabriel, K., “Multiphase Reactor Scale-up for Cu-Cl Thermochemical Hydrogen Production” (in press), International Journal of Hydrogen Energy, 2008

[6] Suppiah, S., Li., J., Sadhankar, R., Kutchcoskie, K. J., “Study of the Hybrid Cu-Cl Cycle for Nuclear Hydrogen Production”, Proceedings of the EIC Climate Change Technology Conference, pp. 231 – 238, Ottawa, Ontario, 2006

[7] Miller, A. J., Duffey, R. B., “Sustainable and Economic Hydrogen Co-generation from Nuclear Energy in Competitive Power Markets”, International Energy Workshop, Laxenburg, Austria, June 24 – 26, 2003

[8] Miller, A. I., “Electrochemical Production of Hydrogen by Nuclear Energy”, Nuclear Production of Hydrogen - Technologies and Perspectives for Global Deployment, Chapter 4, American Nuclear Society, La Grange Park, Illinois, 2004

[9] Lewis, M. A., “Recent Advances in Cu-Cl Cycle Research and Development”, ORF Nuclear Hydrogen Workshop, Oshawa, Ontario, Canada, December 20, 2007